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SAND DEVILS

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SAND DEVILS

By William D. Flower, B.Sc., A.Inst.P.

Introduction.—Sand devils may be described as small whirlwinds which are made visible owing to sand and light vegetable debris being raised into suspension. They appear as rotating columns of sand, sometimes tapered towards the base, the limits of which are generally well defined, and those which attain an appreciable height lean in the direction towards which the wind is blowing. It is known that sand devils occur in desert regions during certain times of the year but in meteorological literature there is little information that is based on actual observation regarding their direction of rotation, dimensions, velocity and direction of progression, duration and annual and diurnal variation of occurrence. Detailed observations of these phenomena have therefore been made at the Meteorological Office stations in Middle East Area and Iraq since the beginning of 1927. The stations from which observations have been received are Aboukir, Heliopolis, Abu-Sueir (1926 to June, 1928) and Ismailia (from July, 1928) in Egypt, Ramleh in Palestine, Amman in Trans-Jordan, and Mosul, Kirkuk (1927 and 1928), Hinaidi, Diwaniyah and Shaibah in Iraq (Fig. 1) while a few observations from the neighbourhood of Khartoum were also recorded by pilots of the Royal Air Force in 1928.

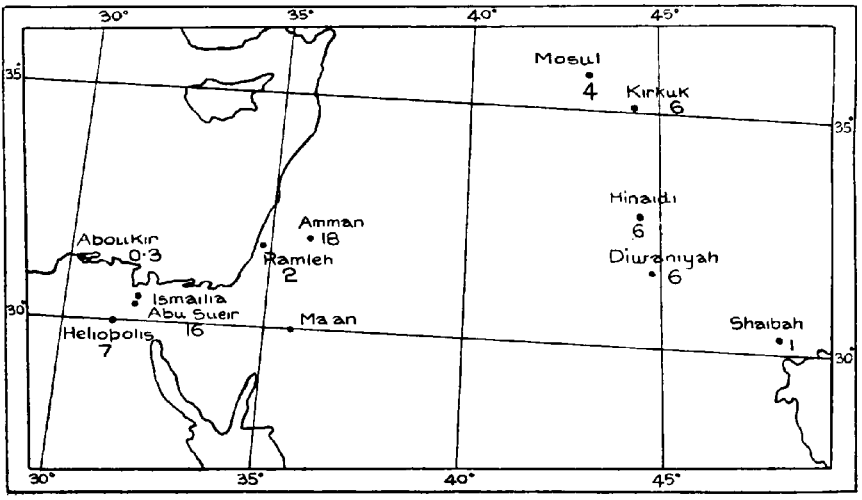


Fig. 1.—Meteorological stations from which reports of sand devils were received together with the mean number observed per year.

The details generally noted were date and time of occurrence, height, diameter, direction of rotation, velocity and direction of progression and duration, together with any other features of interest. The time of occurrence has been entered as zone time in all cases. No attempt has been made to convert to local time at each station as, although for the purpose of summarising the results stations have been grouped together into two areas, the difference in time

between the eastern and western limits of the areas is less than twenty-five minutes in the case of Egypt, Palestine and Trans-Jordan and less than nineteen minutes in the case of Iraq.

Variation of Occurrence.—(*a*) *Annual Variation.*—A tabulation of the number of sand devils reported each month during the period 1927 to 1932 (Table I) shows an obvious maximum during the hot months. In Egypt ninety-three per cent of the total occurred during the months May to September. No sand devils were observed during either January or February and less than one per cent during November and December. In Palestine, Trans-Jordan and Iraq the majority were observed during June to September, the respective figures being eighty-five per cent for Palestine and Trans-Jordan and sixty-eight per cent for Iraq. No sand devils were observed during the three months January to March in Palestine and Trans-Jordan nor during the four months November to February in the case of Iraq.

The positions of some meteorological offices are more favourable than others for observing the development of sand devils in their vicinity, while in some cases (Amman, Ismailia and Khartoum) the area covered by the observations was not restricted to the immediate vicinity of the station. Reports from Khartoum included observations as far north as Atbara, while Amman included some on the Ziza Plain and at Ma'an. Bearing these qualifications in mind the figures given in Table I give a rough idea of the relative frequency of sand devils between one district and another and the mean number observed per year has therefore been entered against the appropriate reporting station on the key map (Fig. 1).

TABLE I.—NUMBER OF SAND DEVILS OBSERVED DURING THE PERIOD 1927 TO 1932

Area	Direction of rotation	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Egypt and Soudan	Clockwise	..	..	2	5	13	9	12	12	11	2	..	1	67
	Counter-clockwise	..	..	..	6	16	14	18	10	14	..	1	..	79
	Total observed	..	..	3	11	30	25	35	26	27	5	1	1	164
Palestine and Trans-Jordan	Clockwise	..	..	..	..	6	13	13	14	7	1	..	..	54
	Counter-clockwise	..	..	..	2	1	13	10	15	18	4	1	1	66
	Total observed	..	..	..	5	7	29	23	34	25	5	1	1	130
Iraq	Clockwise	..	..	6	5	..	5	15	5	10	8	..	..	54
	Counter-clockwise	..	..	1	6	3	11	13	9	8	4	..	..	55
	Total observed	..	..	7	11	6	19	28	14	18	12	..	..	115

It will be seen that sand devils are particularly frequent in the neighbourhood of Amman, Abu-Sueir and Ismailia where large areas of the desert consist of very fine sand.

(*b*) *Diurnal Variation.*—The diurnal variation of occurrence is given in Table II. The fact that the maximum frequency is about one hour earlier in Iraq than in Egypt, Palestine and Trans-Jordan may be associated with peculiarities in the diurnal variation of wind force. The secondary maximum in Iraq about 1600 is probably accounted for by the greater chance of an observer seeing a sand devil about the time for taking meteorological observations. In the Iraq plain, that very hot and humid region at the head of the Persian Gulf, it is the custom to keep indoors during the heat of the day, say between 1200 and 1600, and as normally very little flying is done during this period it is reasonable to expect a marked deficiency of reported occurrences between these hours. There are no reports for the night hours as it is only during the day that sand devils will be visible. There are, however, reasons for thinking that these disturbances occur only under very special conditions at night. The question of probable preponderance of reports about the hours of routine observation is likely to apply to any station. In Egypt, Palestine and Trans-Jordan(1)* routine observations were made at dawn (0400 in winter, 0500 in summer), 0800, 1400 and 2000, and in Iraq at 0500, 0900, 1600(2).

TABLE II.—DIURNAL VARIATION OF OCCURRENCES OF SAND DEVILS 1926 TO 1932

Area	Direction of rotation	0630 to 0730	0730 to 0830	0830 to 0930	0930 to 1030	1030 to 1130	1130 to 1230	1230 to 1330	1330 to 1430	1430 to 1530	1530 to 1630	1630 to 1730	1730 to 1830	1830 to 1930
Egypt, Palestine and Trans-Jordan	Clockwise	3	..	3	6	22	21	20	18	13	9	2	2	1
	Counter-clockwise	..	1	2	9	15	24	35	24	11	11	5	2	..
	Total	3	1	5	16	39	51	58	46	30	30	8	4	1
Iraq	Clockwise	..	..	..	2	5	7	11	9	8	8	3	..	..
	Counter-clockwise	..	..	1	..	8	12	8	9	4	12	2	..	1
	Total	..	..	1	2	13	23	20	18	12	20	5	..	1

All times are zone time.

Rotation.—(*a*) *Direction of Rotation.*—The direction of rotation has been considered to be that which would be observed from a position above the upper limit of the whirl. In the earlier reports the direction of rotation was in most cases reported as either cyclonic or anticyclonic without any qualification as to the position of observation and Durward(3), starting from the hypothesis that the

* The numbers in brackets refer to the bibliography on p. 16.

rotation should be controlled by the earth's rotation, was perplexed by the apparent equality between sand devils of each sense of rotation. Durward drew attention to the possibility of some ambiguity arising in the use of the terms owing to the relative position of the eye and the part of the sand devil observed. Thus a devil viewed from above would be reported as rotating in one sense but in the opposite sense if viewed from below. The terms used by observers, namely cyclonic or anticyclonic, should however be free from ambiguity if the observations are confined to the northern hemisphere but in order to avoid all possibility of misunderstanding observers were requested in 1932 to state the sense of rotation that would be reported on the assumption that the observer was looking down on the whirl from above.

The observations of sand devils during 1932 in Palestine, Trans-Jordan and Iraq were few but the numbers reported at Heliopolis and Ismailia may be used to test the possibility of a systematic error before 1932 on the reported direction of rotation. The figures for that year together with those previously reported (Table III) show that at Heliopolis the rotation is predominantly clockwise, while at Ismailia a counter-clockwise rotation is more frequent and the ratio of one sense of rotation to the other is roughly the same both before and during 1932.

TABLE III.—DIRECTION OF ROTATION OF SAND DEVILS REPORTED DURING 1932 AND DURING THE PERIOD 1927–31

	Direction of rotation	1932	
			1927–31
Heliopolis	Clockwise	18	13
	Counter-clockwise ..	5	4
			1928–31
Ismailia	Clockwise	6	1
	Counter-clockwise ..	33	6

It thus seems reasonable to conclude that no systematic error is involved by considering the direction of rotation as reported prior to 1932 to be other than that which would be noted from above. The figures given in Table I show approximate equality between clockwise and counter-clockwise (when viewed from above) rotation, with a small preponderance in favour of counter-clockwise, thus confirming the result obtained by Col. Gold(4) from a preliminary summary of the reports for the period April to October, 1927.

(*b*) *Speed of Rotation.*—A few isolated estimates of the speed of rotation of sand devils were made either by taking the time for a piece of paper or other light material in suspension to make a certain number of revolutions or by estimating the diameter and also the wind velocity according to the Beaufort Scale on the periphery of

the disturbance. The values obtained (Table IV) vary from 0·06 rev./sec. at the periphery for a broad and shallow whirl to 3·1 rev./sec. for a thinner and taller sand devil.

TABLE IV.—SPEED OF ROTATION OF SAND DEVILS FOR SEVEN SPECIAL CASES

Height	Diameter	Velocity at periphery	
		Angular	Linear
ft.	ft.	rev./sec.	m.p.h.
80	45	0·11	10
500	18	0·26	10
120	90	0·06	12
900	25	0·27	14
300	30	0·31	20
150–300	30	3·14*	32
>1,000	200	0·59*	40

* Report gave the number of revolutions made by the central region in a certain time. Devil assumed to have the form considered in the section on the development of sand devils and core taken to be rotating at the speed reported.

TABLE V.—NUMBER OF OCCASIONS OF SAND DEVILS OF SPECIFIED DIMENSIONS

Diameter	Height in ft.												Total
	<5	5–10	10–20	20–40	40–80	80–150	150–300	300–500	500–1000	1000–2000	2000–3000	3000–4000	
ft.	Sand devils with a clockwise rotation												
<5	2	1	1	..	..	1	1	..	..	..	..	..	6
5– 10	1	1	..	3	2	2	..	1	2	..	..	..	12
10– 20	..	..	1	1	6	5	2	1	1	3	..	..	20
20– 40	..	..	..	2	3	5	3	2	4	1	..	..	20
40– 80	..	..	..	1	2	2	8	3	1	4	1	..	22
80–150	..	..	..	..	..	..	1	4	2	..	..	..	7
>150	..	..	..	..	..	..	..	1	..	..	..	..	1
Total	3	2	2	7	13	15	15	12	10	8	1	..	88
	Sand devils with a counter-clockwise rotation												
<5	9	5	3	1	..	1	1	..	..	..	..	..	20
5– 10	2	9	4	..	1	5	2	..	2	..	..	..	25
10– 20	2	3	2	2	4	3	3	4	3	..	..	..	26
20– 40	..	..	5	2	5	4	2	1	2	2	..	..	23
40– 80	..	..	..	..	1	4	4	1	1	3	..	..	14
80–150	..	..	..	1	1	2	1	2	5	2	1	1	16
>150	..	..	..	..	..	1	1	2	1	1	..	..	6
Total	13	17	14	6	12	20	14	10	14	8	1	1	130

Dimensions, Motion and Duration.—(*a*) *Dimensions.* The methods employed by the observers to make estimates of the dimensions of sand devils varied and in many cases were probably little better than guesses. When the distance of the disturbance from the point of observation could be easily determined the height was obtained in a few cases by observing the elevation of the upper limit with a theodolite and the diameter was deduced from the micrometer reading in the eyepiece but in general the estimates were obtained from a comparison of the size of the whirl and some object of known dimensions in the field of view. The estimated heights and diameters of sand devils exhibit a considerable variation (Table V) ; the former vary from less than 5 ft. to between 3,000 and 4,000 ft., while the diameters range from under 5 ft. to between 200 and 300 ft. No direct relation exists between height and diameter although from the figures it is evident that there have been no occurrences of sand devils of small diameter and great height, and very few of large diameter and small height. In fact, of thirty devils with a diameter between 80 and 300 ft. eleven exceeded 500 ft. in height and five exceeded 1,000 ft.

(*b*) *Velocity.*—The mean forward velocity of sand devils with dimensions between specified limits (Table VI), obtained from the time taken by the disturbance to travel an estimated distance, show that for a devil of specified height the velocity at first increases with increasing diameter but subsequently decreases. The diameter corresponding to the maximum velocity increases with the height of the disturbance. The fastest moving devils seem to be tall and of fairly large cross section although there is evidence of a secondary

TABLE VI.—MEAN FORWARD VELOCITY IN MILES PER HOUR OF SAND DEVILS WITH DIMENSIONS BETWEEN SPECIFIED LIMITS

Diameter	Height in ft.												
	<5	5–10	10–20	20–40	40–80	80–150	150–300	300–500	500–1000	1000–2000	2000–3000	3000–4000	Not stated
ft.													
<5 ..	6	10	17	4	..	21	6	..	..	..	..	..	..
5– 10 ..	15	10	12	14	14	8	9	11	8	6	..	..	..
10– 20 ..	7	10	16	19	16	10	12	9	8	9	..	..	..
20– 40 ..	..	..	11	18	19	13	13	8	10	7	..	..	2
40– 80 ..	..	..	..	15	12	13	11	16	14	9	20	20	20
80–150 ..	..	..	..	..	17	11	4	9	11	15	..	..	..
>150 ..	..	..	..	..	..	13	..	15	10	4	..	..	..
Not stated	7	27	7	10	13	17	18	13	16	20	24	..	..
Mean velocity	8	12	13	12	14	13	13	12	13	11	23	20	11
Mean height	3	8	18	30	60	114	236	470	890	1,740	3,000	3,500	

maximum of velocity for whirls 20 to 80 ft. high and 10 to 40 ft. in diameter. With low values of the forward velocity, less than about 15 m.p.h. (Table VII), sand devils with a counter-clockwise rotation predominate but for higher velocities clockwise whirls are more frequent. The velocity of a sand devil is approximately equal to the mean velocity of the air stream in which it develops. Out of thirty-six occasions when both the forward velocity and the wind velocity were reported the whirl was moving with the velocity of the air stream in twenty-seven cases and differed from it by less than 5 m.p.h. in the remainder.

TABLE VII.—PERCENTAGE FREQUENCY OF SAND DEVILS WITH A FORWARD VELOCITY WITHIN SPECIFIED LIMITS

	Velocity in m.p.h.					Total number of occasions
	<5	5–10	10–20	20–30	30–40	
All reports	9	41	38	11	1	353
Clockwise	5	34	42	18	1	154
Counter-clockwise ..	12	42	37	8	1	169

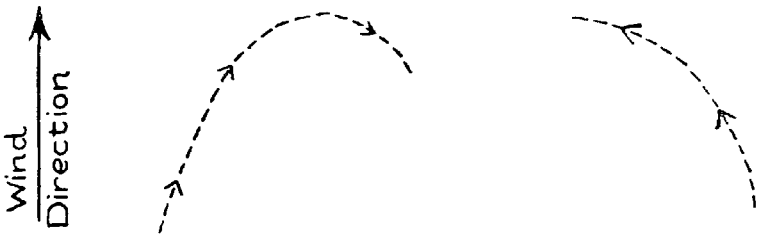
(*c*) *Direction of movement.*—The observations of the directions to which sand devils move (Table VIII) show that in all the regions considered the movement was generally towards some point between east and south.

TABLE VIII.—PERCENTAGE FREQUENCY OF SAND DEVILS MOVING TOWARD DIFFERENT DIRECTIONS

Area	S.	SW.	W.	NW.	N.	NE.	E.	SE.	Station-ary	Number of reports
Egypt, Palestine and Trans-Jordan.	32	6	11	1	2	3	32	19	2	256
Iraq	21	7	2	6	10	3	32	19	..	107

In Egypt the number travelling southwards predominated but in Palestine and Trans-Jordan the majority moved east or south-east. The few reports which included a note of the wind direction prevailing when a sand devil occurred indicate that these disturbances normally travelled in the same direction as the air stream. Of forty-seven whirls where this information is available thirty-three moved in the direction of the prevailing wind while in all but one of the remaining cases the direction taken differed by less than 45° from that of the wind.

(*d*) *Path described by a Sand Devil.*—At Ismailia during 1932 notes were made by the writer on the paths described by sand devils: the paths were invariably curved. Thirty cases of counter-clockwise whirls were observed travelling across wind to the right and in three of them the final track, just before the disappearance of the sand devil, was into the wind (Fig. 2a). Sand devils with a clockwise rotation were observed on only five occasions but in each case the motion was to the left (Fig. 2b). The type of path is similar to that described by whirlwinds starting from the fire front of bush fires(5) and the curvature is that which would be expected if it were due to the effect of friction(6).



(*a*) counter-clockwise rotation (*b*) clockwise rotation

FIG. 2.—APPROXIMATE PATH DESCRIBED BY SAND DEVILS

(*e*) *Duration.*—The time between the observed formation and final dissipation or duration of a sand devil varied considerably (Table IX). A number of disturbances (about 23 per cent) persisted for less than 30 seconds although a few were active for 20 minutes, and as is to be expected the larger sand devils had longer lives. The life of a sand devil increases both for an increase in height and for an increase in diameter (Table X). The direction of rotation and duration (Tables IX and X) considered together show that large sand devils exhibit a preference for a counter-clockwise rotation.

TABLE IX.—NUMBER OF OCCASIONS OF SAND DEVILS WITH A DURATION BETWEEN SPECIFIED LIMITS

Direction of rotation	Duration in minutes									
	<0·5	0·5 to 1·0	1·0 to 2·0	2·0 to 4·0	4·0 to 6·0	6·0 to 8·0	8·0 to 10·0	10·0 to 15·0	15·0 to 20·0	>20
Clockwise	19	19	14	10	13	6	4	3	..	..
Counter-clockwise ..	25	12	12	17	6	4	15	5	1	..

TABLE X.—MEAN DURATION IN MINUTES OF SAND DEVILS WITH SPECIFIED DIMENSIONS

Diameter	Height in ft.												Mean duration
	<5	5–10	10–20	20–40	40–80	80–150	150–300	300–500	500–1000	1000–2000	2000–3000	3000–4000	
ft.													
<5 ..	0·7	0·3	1·0	..	..	..	3·0	..	..	..	..	..	1·1
5– 10 ..	..	0·3	3·0	0·5	..	5·5	4·0	5·0	10·0	..	..	..	3·9
10– 20 ..	0·3	2·0	2·7	..	0·7	3·4	4·0	10·2	8·5	..	..	..	4·7
20– 40 ..	..	..	1·3	10·0	5·1	3·1	6·0	10·3	7·7	9·2	..	..	6·6
40– 80 ..	..	..	..	2·0	4·0	1·8	4·0	4·7	5·0	10·3	7·0	8·0	5·4
80–150 ..	..	..	..	..	1·0	6·5	3·0	2·7	10·0	13·3	..	..	7·2
>150 ..	..	..	..	..	..	..	..	8·5	6·0	15·0	..	..	9·5
Not stated	..	..	3·9	0·4	2·9	2·6	1·4	1·0	1·3	2·5	..	..	..
Mean duration	0·7	0·9	2·5	1·9	3·0	3·2	3·0	5·1	5·1	9·7	7·0	8·0	

The Lapse Rate of Temperature Associated with the Occurrence of Sand Devils.—Readings of temperature at approximately 4, 50, 150 and 200 ft. above the desert at Ismailia were recorded during 1932 by a special installation which will be described elsewhere and the lapse rate of temperature over the hours that sand devils occurred at Ismailia were obtained from these readings (Table XI). These lapse rates show that when sand devils occurred the lapse rate slightly exceeded the mean for the period and this is especially marked below 50 ft.

TABLE XI.—MEAN VALUES OF THE LAPSE RATE AT ISMAILIA IN °C./100M. DURING 1932 AT THE HOURS WHEN SAND DEVILS WERE OBSERVED

Zone time	10	11	12	13	14	15	16	17	18
	3·6 to 201·1 ft.								
Mean for sand devil occurrences ..	3·5	4·0	4·3	4·5	4·3	4·2	4·0	3·2	2·1
Mean Apr.–Sept. ..	3·7	4·0	3·9	4·1	4·4	4·2	3·7	2·9	1·8
	3·6 to 53·1 ft.								
Mean for sand devil occurrences ..	9·4	10·6	11·8	12·6	12·3	12·1	10·9	7·8	4·9
Extremes on sand devil days ..	14·5	14·7	14·4	14·9	15·6	14·2	13·4	10·1	9·5
Mean Apr.–Sept. ..	9·2	10·7	10·4	10·8	12·0	11·7	10·1	7·3	3·6

The lapse rate up to at least 200 ft. on occasions when sand devils occurred was always super-adiabatic and between 4 and 50 ft. the lapse rate during the early afternoon on these days exceeded twelve times the dry adiabatic. The extreme lapse rates on days when sand devils developed frequently exceeded 14° C./100 m. between 4 and 50 ft. indicating a very high degree of instability.

Vertical Air Currents.—In a few isolated cases rough estimates were made of the vertical currents associated with sand devils. These rough estimates were obtained by noting the time taken for small pieces of paper or other light material to be carried upwards through an estimated distance and varied between 200 and 500 ft. per minute. An exceptional case of intense vertical currents associated with a sand devil occurred on an occasion when an aircraft was forced downwards with an acceleration exceeding that due to gravity(7).

Changes in Meteorological Elements Associated with the Passage of Sand Devils.—A sand devil seldom passed over or sufficiently close to a meteorological station for it to affect the instruments but for the few occasions that observations are available certain consistent changes were observed in the wind, temperature and pressure (Table XII).

TABLE XII.—NUMBER OF OCCASIONS OF SPECIFIED CHANGES IN METEOROLOGICAL ELEMENTS AT THE PASSAGE OF A SAND DEVIL

Change	Wind		Temperature	Relative humidity	Pressure (micro-barograph)
	Velocity	Direction			
Veer or increase ..	30	12	..	2	2
Back or decrease	..	1	5	..	12

In every case a temporary slight veer was observed in the wind direction and with one exception the wind velocity increased as the sand devil passed the anemometer. This increase took the form of an isolated gust in 14 cases and bore no relation to the general run of the velocity trace. These gusts were noteworthy because of the magnitude of some of them and an outstanding example occurred at Amman on July 15, 1930, when with a W. by S. wind of mean velocity about 20 m.p.h. a sand devil gave an isolated gust of 59 m.p.h. This devil was 2 ft. in diameter, 150 ft. high, was travelling at about 25 m.p.h. from west to east and passed over or very close to the anemometer vane. Changes in temperature, pressure and relative humidity were noted on too few occasions to permit of any

definite conclusions but it is of interest to note that a fall of pressure of 1·0 mb. was recorded at least twice although no noticeable change was associated with the disturbance at Amman on July 15, 1930.

The Development of Sand Devils.—Jeffreys(8) and Low(9) have discussed on theoretical grounds the instability of an incompressible fluid heated from below and arrive at the conclusion that conditions are stable so long as the lapse rate does not exceed the adiabatic. Jeffreys(10) has shown that this result applies also to a compressible fluid and further(8) that the effect of rotation of the fluid as a whole on the above value of the lapse rate can be neglected when the horizontal dimensions are small such as might be experienced with waterspouts, tornadoes or dust devils. It is known that sand devils normally occur when the lapse rate in the layers of air near the ground is superadiabatic and since such conditions are thermally unstable there will be potential energy available for maintaining and developing any eddy that may originate in the air stream. Sand devils may be likened to vortices or eddies in the atmosphere which have been made visible by sand carried up into suspension and it should therefore be sufficient to determine the conditions favourable for the development of intense vortex or eddy motion in the air layers near the ground in order to obtain an idea of the method of formation of sand devils. The air near the ground contains a large number of eddies in various stages of decay and those which occur when a mass of air flows over obstacles are likely to be the most important in sand devil development.

Before going further it is necessary to speculate as to the form of the rotating column of air forming the devil. It may be considered to be either a column of air rotating with uniform angular velocity (ω) or else to consist of a core in uniform rotation surrounded by a region in which the velocity (v) decreases as the distance (r) from the centre increases. The latter form seems to be the more probable and the kinetic energy of a devil consisting of a solid core and a simple vortex will now be computed.

Assume that a sand devil consists of a core of radius r_o in " solid rotation " with angular velocity ω and a surrounding mass with the velocity at any point inversely proportional to the distance of the point from the axis, starting from the maximum velocity at r_o, then if the vortex extends to a distance equal to n times the radius r_o, the kinetic energy is given by :—

$$\int_o^{r_o} 2\pi r\,(\tfrac{1}{2}\omega^2 r^2)\,\rho h\cdot dr \;+\; \int_{r_o}^{nr_o} 2\pi r \tfrac{1}{2}\left\{\frac{\omega r_o\cdot r_o}{r}\right\}^2 \rho\, h.dr$$

$$= \pi\omega^2 h\rho\left[\int_o^{r_o} r^3\cdot dr + \int_{r_o}^{nr_o} r_o^4\frac{dr}{r}\right]$$

$$= \pi\,\omega^2 h\rho r_o^4\,[\tfrac{1}{4} + \log_e n]$$

where h is the height of the sand devil and ρ is the density of the air.

Assume that a sand devil is the special case where the vortex extends to a distance equal to four times the radius of the circle of maximum velocity, i.e. where $n = 4$, then the kinetic energy of the whirl will be

$$\pi h \rho v_o^2 r_o^2 \times 1{\cdot}64$$

Consider a column of air, height h and radius r, in which the lapse rate is superadiabatic and let the temperature and pressure at the top be T and P respectively. Assume that this column of air is set rotating and the energy available is that due to a reduction in the lapse rate then, neglecting radiation changes, the available energy will be equal to the change in heat content of the air column plus the increase in its gravitational energy due to the sinking of the centre of gravity of the air. If α and β are the initial and final lapse rates respectively the change in energy brought about by the change in temperature will be equal to $\frac{1}{2}\pi r^2 h^2 \rho (\beta - \alpha) c_p$, where c_p is the specific heat of air at constant pressure. The change in gravitational energy can be shown to be equal to $\pi r^2 h^3 \rho g (\beta - \alpha)/3T(11)$ and since this is insignificant compared with the energy available through the change in temperature of the column it can be neglected.

Consider the case where the lapse rate is initially five times the adiabatic for dry air and finally equal to the adiabatic. If the initial temperature at the base is 100° F., the radius of the eddy, 5 ft. and the height 100 ft., the potential energy available is $3{\cdot}73 \times 10^6$ foot poundals. Equating this to the expression for kinetic energy already obtained, and substituting for h and r_o, the angular velocity of the core is found to be 32·04 rev./sec., and this is reduced to 2·0 rev./sec. at the periphery of the eddy. The corresponding tangential velocity of 55 m.p.h. would be superimposed on the velocity of translation and if the latter was 15 m.p.h. a minimum velocity of 70 m.p.h. would be associated with the passage of the eddy.

Some eddies will be fairly active when passing over areas of loose fine sand with the result that some sand will be carried upwards into suspension and share its heat with the air of the eddy. If the temperature of the sand is very high this may result in an increase of the angular velocity. If it is assumed that the sand does not raise the temperature of the air in the eddy then unit volume of sand will be capable of supplying heat equivalent to $\rho_s s \Delta T' \times 99{\cdot}4 \times 0{\cdot}55$ foot poundals, where ρ_s and s are respectively the density and specific heat of sand and $\Delta T'$ is the initial difference in temperature between the sand and the eddy in degrees Fahrenheit. If the temperature of the sand is 18° F. above the mean temperature of the eddy and an amount of sand equal to 1×10^{-6} times the volume of the eddy is drawn up into suspension (i.e. an amount equivalent to a layer of sand about 0·001 inch thick at the base of the eddy) the heat liberated will be equal to $11{\cdot}1 \times 10^4$ foot poundals.

This energy would suffice not only to compensate the eddy for the work done in raising the sand into suspension and in setting it rotating at the same speed as the air in the eddy, but also to supply $10{\cdot}2 \times 10^4$ foot poundals for increasing the speed of rotation of the resultant sand devil. This amount is very small however and would only increase the angular velocity at the periphery by 0·05 rev./sec. so that the effect of the hot sand is insignificant compared with the effect of the superadiabatic lapse rate. The increase in angular velocity due to raising hot sand becomes less the greater the amount of sand involved. An analysis of the devil responsible for the gust of 59 m.p.h. at Amman on July 15, 1930, made on the assumption that the gust represented the velocity at the periphery superimposed on the velocity of translation gives the angular velocity at the periphery as 5·6 rev./sec. If the heat lost by the sand drawn into suspension was just sufficient to raise its centre of gravity and to set it rotating with the speed of the eddy, a lapse rate up to 150 ft. equal to only 2·7 times the dry adiabatic value would have been sufficient to endow the air in the eddy with the potential energy necessary to promote this speed of rotation.

An eddy originating in an air mass will increase in height as long as there is potential energy available for its development in the air layers above it so that if the lapse rate is superadiabatic up to a height of 2,000 or 3,000 ft. sand devils would be expected with heights of this order. Observations of temperature above 200 ft. are not available for days on which sand devils are known to have occurred but a few observations of upper air temperatures taken between 1300 and 1430 local time over Lower Egypt show that there were occasions during the months April to August when the lapse rate was superadiabatic up to 3,000–4,000 ft. and it is probable that on such occasions tall sand devils develop. At night the mean lapse rate of temperature up to 200 ft. at Ismailia is negative(12) so that eddies originating in the surface layers would degenerate owing to the lack of potential energy for their development. Sand devils formed in the way suggested could not therefore exist at night.

A large number of observations of sand devils formed as described above and covering a sufficiently large area should contain equal numbers with a clockwise and with a counter-clockwise rotation, but this would not be the case for observations made at one point unless the obstacles were symmetrical about it. With a northerly wind and obstacles to the west of a station clockwise rotation would be expected to show the greatest frequency and with obstacles to the east a counter-clockwise rotation would predominate. Since a northerly wind blows with great constancy over Lower Egypt in summer this may be the explanation of the apparent anomalous behaviour of sand devils as indicated by the observations from Heliopolis and Ismailia. The town and aerodrome at Heliopolis all lie to the west of the meteorological station while from north through east to south-west is open desert rising to the Mokattam Hills

situated at a distance of about 6 miles south of Heliopolis but at Ismailia all buildings and vegetation lie between north-east and south through east with open desert in all other directions.

The formation of a few sand devils may occur when conditions exist similar to those which, over the sea, would be favourable for the development of waterspouts. Devils formed in this way would be physically the counterpart of tornadoes and would revolve in a counter-clockwise sense. They would develop at the boundary between warm and cold air currents and be likely to occur in families along a wide front. This method of formation would account for the number of devils reported with a counter-clockwise circulation exceeding those rotating in a clockwise sense and also explains the occasional development of a line of sand devils. As many as eight devils in line have been observed moving across the desert and the direction of rotation of the individual devils was counter-clockwise in every case. A number of sand devils in line is not a frequent occurrence in either Egypt or Iraq but a summary of the few reports available is given below (Table XIII).

TABLE XIII.—NUMBER OF OCCASIONS WHEN A SPECIFIED NUMBER OF SAND DEVILS IN LINE WERE OBSERVED

Station	Number of Sand Devils in line							
	2	3	4	5	6	7	8	Doubtful
Heliopolis	1	1	..	..	..	..	..	..
Abu-Sueir	1	1	..	..	..	1	..	3
Amman	..	2	1	..	..	..	1	1
Hinaidi	1	2	1	1	1	..	..	..

The fact that in one or two cases a devil appeared to be moving below and along with a cloud suggests that there may be extremely rare occasions when the upper limit of the core of a sand devil is made visible by the condensation of water drops due to adiabatic cooling produced by the lowering of pressure by elevation.

Conclusion.—An examination of reports of the occurrence of sand devils during 1927–32 in Egypt, Palestine, Trans-Jordan and Iraq shows that the direction of rotation may be either clockwise or counter-clockwise with a slight preference for the latter sense. They occur mainly from May to September in Egypt and from June to September in Palestine, Trans-Jordan and Iraq, and have never been observed during January or February in Egypt, January to March in Palestine and Trans-Jordan or November to February in Iraq. Sand devils occur when the lapse rate in the lowest layers is superadiabatic and exhibit a maximum frequency between 1000 and 1600. The occurrences outside these hours are few and limited to a period of two hours at either end of the above mentioned period.

A method of formation has been suggested which essentially depends upon the existence of eddies in the air stream of sufficient intensity to pick up particles of fine sand and light vegetable debris.

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